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Cite as: AIP Conference Proceedings **2048**, 030011 (2018); https://doi.org/10.1063/1.5082069
Published Online: 11 December 2018

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Computer Simulation of Operation of an Open Geothermal System Consisting of Multiple Wells

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Abstract. The difficulties related to open loop geothermal systems using includes, in particular, the fact that there is a reverse injection of the cold water through an injection well into an underground aquifer from which hot water is extracted. This necessity for an injection well presence is caused the thermal water from an underground reservoir possible to be high mineralize and to contain toxic compounds and metals, and in most cases one have to avoid to discharge these waters into ground surface natural water systems. An open loop geothermal system of three wells is considered, which can be both productive and injection wells. The developed algorithms and programs allow to select an optimal system configuration of three wells for a specific geothermal deposit. The results of numerical calculations for various variants of the geothermal system are presented.

INTRODUCTION

Exploration and development of new energy resources has always been a big part of human activity. At present, energy saving technologies are becoming more urgent due to the depletion of fossil fuel reserves. Providing heat supply by new generation energy sources has several advantages in compare with the fossil fuels burning. In addition to significant reduction in energy costs for life support of buildings and structures, the energy saving technologies and systems are supposed to be more ecological and autonomous. An effective direction is the use of geothermal energy, which means thermal energy contained in the bowels of the earth. The so-called ground coupled heat exchanger technologies are related with the Earth's energy using [1]. It is the life support of buildings that has the most promising area of application of energy saving technologies that use renewable energy sources.

Inspite of the heat content of the ground in comparison with water is generally higher, since the thermal energy of the surface layers of the earth is affected by the solar energy incident on the surface, but the impact of solar radiation and outdoor temperature is not constant depending on the time of year and day, so the temperature of the upper layers of the earth changes under the influence of these factors. In different regions, the depth of penetration of variations in air temperature and solar radiation is in the range from a few centimeters to two and a half meters, and has no effect at the depth of more than 15–20 m. Below this depth, the temperature of the soil layers is affected only by the thermal energy emanating from the interior of the Earth, and it does not depend on seasonal variations, and the heat movement is related, in particular, with ground waters filtration in porous soils.

Geothermal systems serve for the thermal energy delivering from the bowels of the earth, and as a whole is a production facility that includes a reservoir (aquifer) of geothermal waters throughout the whole service life, that is a geological component with changing characteristics during operation. The source of thermal energy can be groundwater even with relatively low temperature. The possibility of using geothermal water in heat and air supply systems is determined by comparing their technical and economic indicators with the indicators of traditional heat sources. Taking into account the type and quantity of consumers of geothermal energy, their mutual location and the need to trigger the thermal potential of geothermal water, the principle, geothermal heat supply scheme.

An important task is to correctly determine the basic parameters for the design of a geothermal system at the initial stage of the project with using the known characteristics of the reservoir and the forecast of their change. Mathematical models and numerical simulations are used quite widely for these purposes [2, 3].

Proceedings of the 44th International Conference on Applications of Mathematics in Engineering and Economics
AIP Conf. Proc. 2048, 030011-1–030011-5; https://doi.org/10.1063/1.5082069
Published by AIP Publishing. 978-0-7354-1774-8/$30.00

The methods of using and application of geothermal energy depend on the temperature of the water in the reservoir to be developed. A significant part of Russia is characterized by the presence of natural low- and medium-temperature (50–150°) reservoirs, lying at depths of 200 to 3000 meters. Features of such reservoirs, making it difficult to be effectively used, are the followings: the remoteness of geothermal deposits from the points of application; the decreasing in production rate during intensive operation; the intensive scale formation in systems with high mineralization of geothermal waters; intensive corrosion of metal pipelines and equipment due to the saturation of geothermal waters with aggressive gases; harmful impact on the environment of the waste water. An effective thermal potential of the systems using is provided by complex schemes of geothermal heat supply.

There are two main types of geothermal systems: open loop and closed loop systems [4]. The closed loop system deals with a fluid circulating in pipes through the ground and back through the heat pump. The open loop system uses a water well pump to deliver the water and return the used water back to the aquifer. The injection of waste geothermal water into production reservoirs is an effective method of maintaining the pressure and filling of the aquifer and, in addition, protecting the environment from the harmful effects of highly mineralized thermal waters. In this paper an open geothermal system with five wells is considered in view to the interference of thermal water flows. A mathematical model and numerical simulations are presented.

MATHEMATICAL MODEL

We will consider a geothermal cyclic open loop system (GTS), consisting of two types of wells: production wells, which deliver hot water from the deep aquifer, and injection well, which pumps the waste cold water into the productive layer. We will consider a net with 4 production wells (red color) and one injection well (blue color) in a square area. The research objective is to investigate influence of positions of the wells and the flow of cold water on producing temperature. As four basic positions of the producing wells are considered and the injection well is at a vertex of the area. The outlines are presented in Figures 1(a–d) for the four cases.

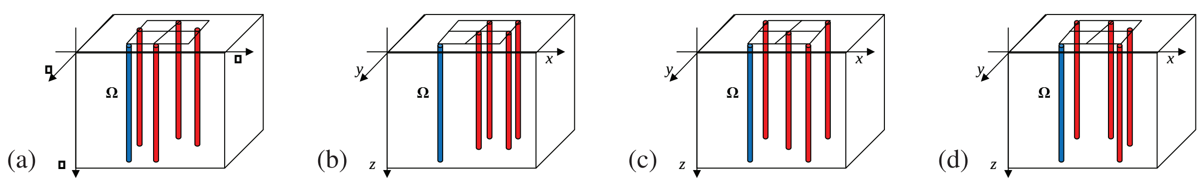

FIGURE 1. The considered well systems: the injection and producing wells are blue and red, respectively.

In simulations of underground flow, Darcy's law and law of mass conservation (continuity equation) are used [5]. A convection-diffusion equation with dominant diffusion due to low velocity of filtration is considered. Let $T(t, x, y, z)$ be temperature in the aquifer. Thermal exchange is described by equation

$$\frac{\partial T}{\partial t} + b\left(\frac{\partial T}{\partial x}u + \frac{\partial T}{\partial y}v + \frac{\partial T}{\partial z}w\right) = \lambda_0 \Delta T, \tag{1}$$

here $b = \dfrac{\sigma\rho c_f}{\rho_0 c_0(1-\sigma) + \rho c_f \sigma}$, $\lambda_0 = \dfrac{\kappa_0}{\rho_0 c_0(1-\sigma) + \rho c_f \sigma}$, ρ_0 and ρ_f are density of aquifer soil and of water, c_0 and c_f are specific heats of aquifer soil and of water, κ_0 is thermal conductivity coefficient of soil, σ is porosity, $\mathbf{V} = (u, v, w)$ is a vector of velocity of water filtration in the soil. The aquifer has an initial temperature T_0 and in injection well temperature is set as "cold water" with temperature T_1, which returns from production well after using.

To compute the velocity we use pseudo-viscosity method with splitting by physical processes [6]. We solve an equation for pressure $p = p(t, x, y, z)$

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = 0 \tag{2}$$

with the following boundary conditions for the surfaces of injection and producing wells:

$$P(t, x, y, z)\Big|_{injection} = P_1 - \rho g z, \quad P(t, x, y, z)\Big|_{production} = P_2 - \rho g z. \tag{3}$$

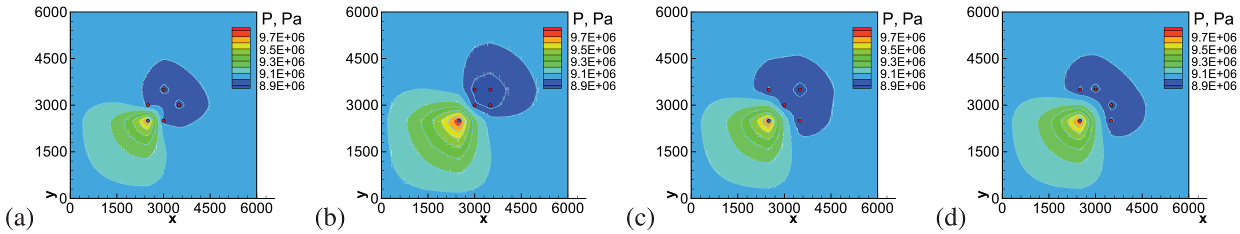

FIGURE 2. Pressure field in the computational in a horizontal plane.

Due to low velocity of filtration we can use a steady-state flow to describe convective transport terms in equation (1). Following [6] to compute the components of velocity we may use the following equation for the previously constructed pressure field:

$$\frac{\partial p}{\partial t} + \nabla \mathbf{V} = 0. \tag{4}$$

The equations (1)–(4) for temperature and pressure in aquifer is solved using a finite difference method based on an approach of works of A.A.Samarskii and P.N.Vabishevich [7]. A finite difference method is used with splitting by the spatial variables in three-dimensional domain to solve the problem. We construct an orthogonal grid, uniform, or condensing near the ground surface and to the surfaces of injection and production wells. The original equation for each spatial direction is approximated by an implicit central-difference scheme and a three-point sweep method to solve system of linear differential algebraic equations is used. This approach was successively used for the problems of describing a thermal trace from underground pipeline taking into account filtration and evaporation of fluid from soil surface [8, 9]. After finding the pressure field, a vector of velocity of filtered water is determined in the aquifer [10, 11, 12]

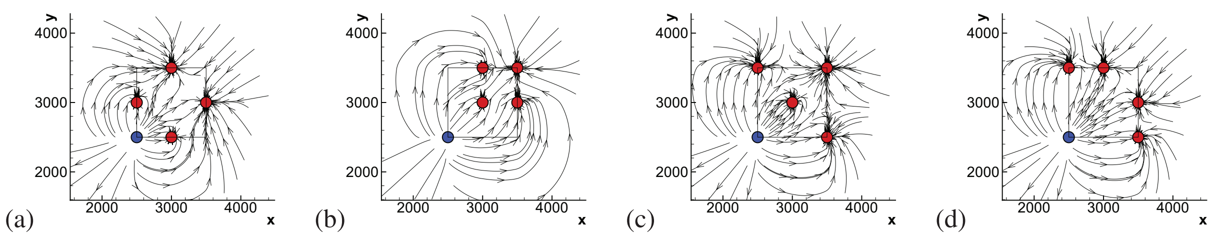

FIGURE 3. Streamlines of water flow filtration in a horizontal plane.

In Figures 2 and 3 a computed pressure field and velocity streamlines are shown, respectively. The figures show a horizontal slice of the field. To complete the problem statement it is necessary to set boundary conditions at the lateral boundaries. For numerical simulations as a rule there used very large horizontal sizes of the computational area to avoid influence of zero flux boundary conditions [13, 14]. But for upper and lower boundaries it is possible to use conditions of fixed temperature and geothermal flux boundary conditions [14]. The research objective is to investigate influence of the producing wells positions the temperature the wells.

RESULTS OF NUMERICAL SIMULATION

Let consider a porous soil layer as a computational area. The layer sizes are 6000m·6000m·50m. Thermal parameters of the aquifer are the following: thermal conductivity is 2,00 [W/(mK)], density is 1000,0 [kg/m^3], specific heat is 4,18 [J/(kg K)], volumetric heat is 2150,0 [J/(m^{3}K)], filtration velocity is $1{,}7 \cdot 10^{-5}$ [m/s], porosity is 0,241. Temperature in aquifer is 95°C, the temperature of injected water is 55°C. There are four production wells in a square area with the edge of 1000 m. Radius of the wells is 0,012m. Four variants of the producing wells in a rectangular net are considered with the distance between the vertices of 500 m, the position are presented in Figure 1. In the figures the positions of injection and production wells are denoted by blue and red circles, respectively.

The pressure in the wells will be proposed as 1200 kPa in the injection well and 300 kPa in the production wells, so that the pressure difference will be 1500 kPa. In Figure 2 the pressure fields in a horizontal plane are shown. The variants notations (a)–(d) correspond to the mentioned above. The simulated water filtration process is suggested to be steady-state and be valid during all the time of the system exploitation. In Figure 3 the stream lines of the velocity fields in a horizontal plane are shown for the same cases. The isobar lines in Figure 2 and directions of streamlines in Figure 3 show the zones of hot water collection and allow to estimate the surface water intake regions.

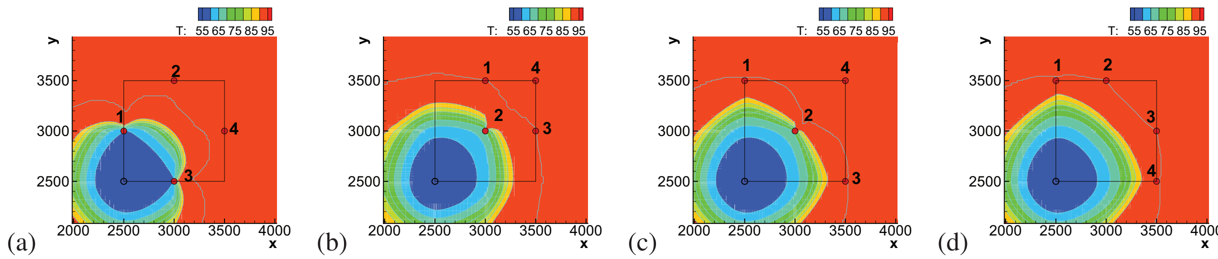

FIGURE 4. Thermal field for 10 years of simulations in a horizontal plane.

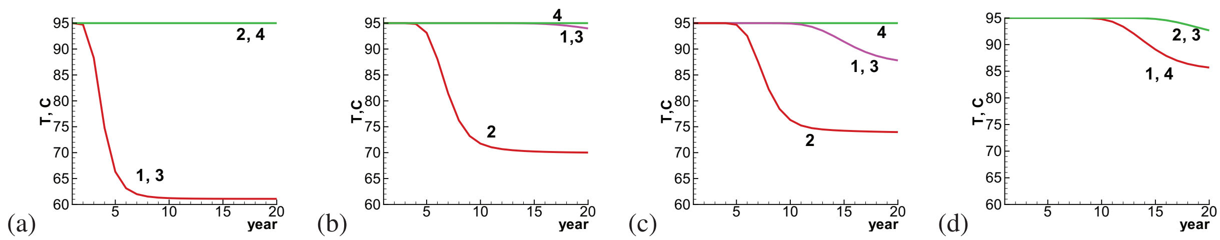

FIGURE 5. Temperature in the production wells during 20 years.

The areas of producing wells for variants (a)–(d) may be characterized as diamond (D), small square (S), long triangle (T), and arch (A), with respect to the positions of the producing wells. In Figure 4 the thermal fields are shown for 10 years of simulations. In Figure 6 the temperature changes in the wells pointed in Figure 5 are presented. The numbers in the figures denote to the producing wells.

D-area (Figure 4a) is most close to the injection well, and wells 1 and 3 work as a barrier for cold water. In S-area(Figure 4b) and T-area(Figure 4c) the barrier is holded by well 2, but the distance from the injection well is larger than in D-area. In A-area(Figure 4d) the producing wells are approximately at the same distance from the injection well. The temperature profiles (Figure 5) show the crucial temperature distribution during the wells exploitation. The barrier wells have a lower life period, but prevent the temperature decreasing in the others. The distance between the intake area of the wells is essential.

CONCLUSION

Geothermal systems are a renewable energy source and serve for the thermal energy delivering from the bowels of the earth. The delivering of the thermal water from an underground aquifer is possible to be realized as a multiple wells system. For effective development of an open loop geothermal system a mathematical model and numerical algorithm are proposed. The simulations include the water filtration in a porous soil and temperature changes in the aquifer due to the waste water injection under the pumps operation. The dynamics of changes in the temperature of hot water in producing well depends on various parameters. The main parameters are the distance between the wells in the productive layer and the pressure difference for two wells system. For the system, consisting of a numbers of wells, the relative position of these wells also have to be taken into account. The simulations allows to estimate the life time of the system and to specify a feature and characteristics of the well to be used. The producing wells closest to the injection well may be used as a barrier for the cold water.

ACKNOWLEDGMENTS

The work was supported by Russian Foundation for Basic Research 16–01–00401 and program of scientific research UrB RAS 18–1–1–8.

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